THE MORPHOLOGICAL DEVELOPMENT OF ALPINE VALLEY HEADS IN THE ANTARCTIC PENINSULA

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ABSTRACT

Glaciation has continued in Antarctica for longer than anywhere else on Earth, so the long-term development of glaciated landforms can be investigated. Complex alpine valley heads up to 36 km wide are found in the Antarctic Peninsula. The largest of these may represent an advanced stage of alpine glaciation, having evolved from the earliest corries which could have developed around the early Oligocene. This study is based on a morphometric analysis of the plan form of 1680 alpine valley heads. This is a much larger sample than used by any previous study. Skewed distributions of dimensional properties (width, length and area) suggest that small corries are continually being added to the population, as older ones are enlarged and some eliminated by coalescence and ice sheet erosion. Very large features are found only in parts of Graham Land and Alexander Island, where lack of high-level ice sheet erosion has allowed the forms of mountain glaciation to dominate the landscape. The attainment of an equilibrium planform shape is suggested by the persistence of an equidimensional form, the development of characteristic or limiting values of other morphometric properties, e.g. planform closure and basin order, and by the intercorrelation of morphometric properties. A combination of branching and coalescence is fundamental in the development of corries. The latter results both in widening, which counteracts the tendency towards lengthening observed by other workers, and also in a limit to basin complexity.

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KEY WORDS: glacial erosion; corrie (cirque); alpine valley head; Antarctic Peninsula; planform morphometry; long-term landform evolution

INTRODUCTION

Corries (cirques) are one of the most characteristic landforms of mountain glaciation. Previous research has initiated many controversies about the way in which they develop over time. Debate has centred on four issues:

(i) what is the relationship between growth in width, length and depth, and with this the relative contribution of glacial and periglacial processes (White, 1970; Derbyshire and Evans, 1976; Olyphant, 1981);
(ii) whether corries become simpler or more complex in planform (Hobbs, 1910, 1921; Grove, 1958; Linton, 1963; Evans, 1969);
(iii) whether or not a time-independent or equilibrium form develops (Linton, 1963; Sugden, 1969; Gordon, 1977);
(iv) how the development of corries influences whole landscapes.

For example Hobbs (1910, 1911, 1921) and Linton (1963, 1964) suggested models for the progressive destruction of previous landscapes by mountain glaciation. Hobbs' paper 'Cycle of mountain glaciation' has been widely criticized, though Linton's have received little comment.

Morphometric analysis of large samples of landforms is needed for the thorough knowledge of morphology, which is fundamental in understanding landform development. It is also important to know what different authors have included in their working definitions of particular landforms.

Simple corries have been defined morphologically by Evans and Cox (1974) and genetically by Haynes (1968). Lewis (1960) described the characteristics of corrie glaciers in detail. These may become the heads or tributaries of valley glaciers. In alpine areas there may also be glaciers which are larger and less steeply sloping

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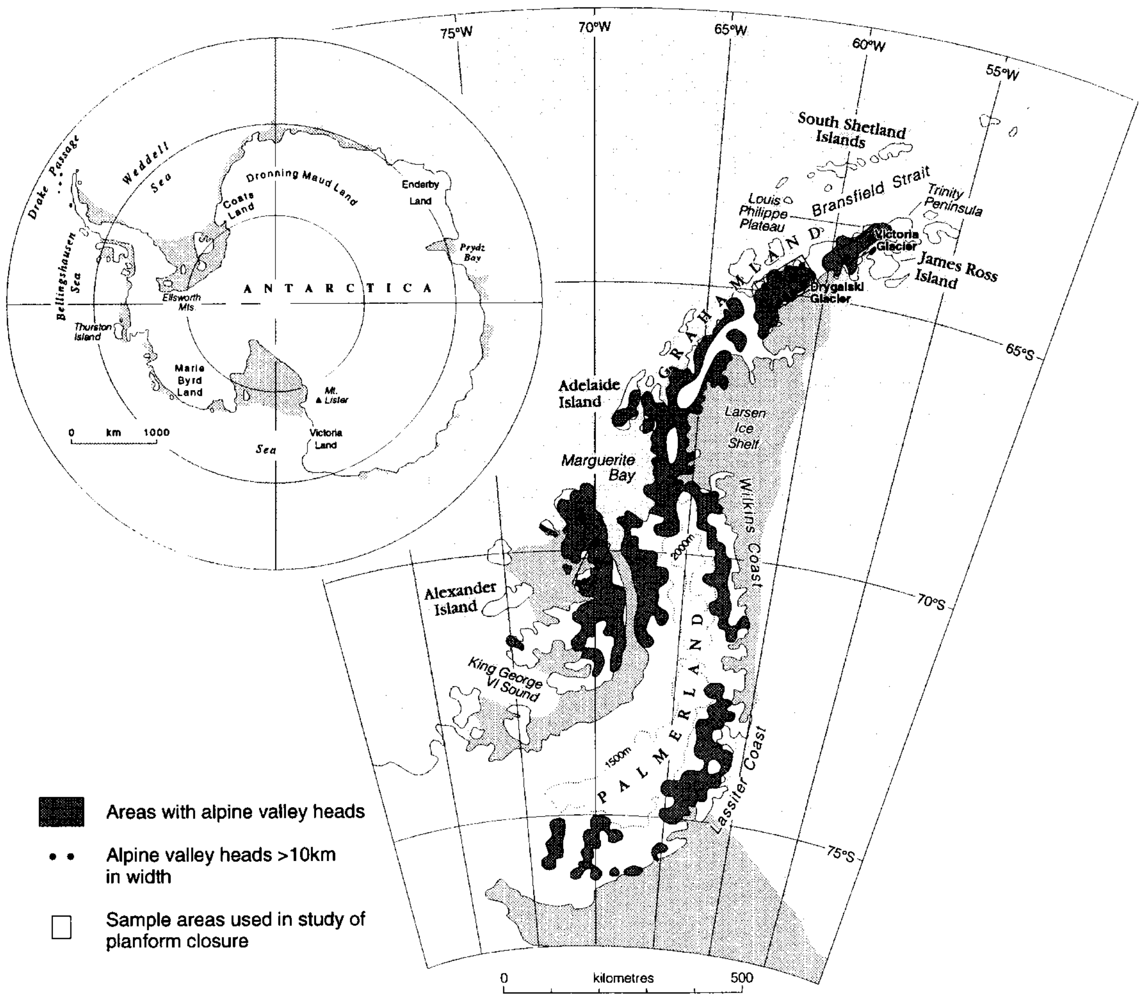

Figure 1. Location map

than classic corrie glaciers, although still headed by a steep rockwall (Linton, 1963). As a result some authors have also recognized more complex corrie forms. Gordon (1977) distinguished ‘cirque complexes’ and ‘cirque troughs’ from simple corries in Scotland. ‘Cirque–trough head combinations’ were described by Ahlmann (1919) in Norway and Evans (1974) in British Columbia. Haynes (1977, 1995) used the term ‘alpine valley head’ to incorporate all these types of landforms, following Linton’s subdivision of glaciated valleys into ‘Alpine’ and ‘Icelandic’ types (Linton, 1963). When authors use the terms ‘corrie’ or ‘cirque’, it is not always clear whether or not they are including more complex forms, so results of morphometric analysis may not always be comparable.

To date, most investigations of large samples of corries have been concentrated in the temperate and subarctic belt of the northern hemisphere (e.g. Temple, 1965; Haynes, 1968; Sugden, 1969; Andrews and Dugdale, 1971; Unwin, 1973; Aniya, 1974; Trenhaile, 1976; Graf, 1976; Vilborg, 1977; Gordon, 1977; Evans, 1977; Embleton and Hamann, 1988), though there are some from the tropics and mid-latitude southern hemisphere (e.g. Clapperton, 1971; Derbyshire and Evans, 1976; Marker, 1991). By contrast, there have been few studies in Antarctica, using statistically significant numbers of individuals. Andrews & LeMasurier (1973) studied eight basins and Holmlund and Näslund (1994) studied twelve, so the only investigations of large samples have been those of Aniya and Welch (1981) and Haynes (1995). The latter used all alpine valley heads

in the Antarctic Peninsula which could be identified on satellite imagery according to the criteria for traditional corries and corrie complexes. The present paper is based on 1680 alpine valley heads in the Antarctic Peninsula, south of 63°30′S, including those used in the above study, with the addition of every feature, however large, which could be found to fit the broad definition of an alpine valley head, i.e. they had to have sharp-crested headwalls, with little sign of erosion by overflowing ice. They are the type of features which Linton (1964) had described on the southeast side of the Louis Philippe Plateau in NE Graham Land as 'broad glacial streams heading in spectacular amphitheatres, walled by rock cliffs'. On the west some of these form high-rimmed coastal embayments. Those valleys which showed signs of considerable erosion of the crests of their encircling walls by ice streams were rejected. These were also morphologically different, being much more elongated, often with a very irregular, rather than an armchair-shaped ground plan.

It is a pity, in view of the debates about corrie development, that research on them in Antarctica has been so limited in scope, since glaciation there has continued for longer than elsewhere, probably since the mid-Eocene (Hambrey *et al*., 1989; Birkenmajer, 1987, 1991) and possibly even the Cretaceous (Robin, 1988; Bartek *et al*., 1992). This contrasts with the onset of glaciation in southern Greenland around 14–10 Ma BP (mid-Miocene) (Eldholm *et al*., 1987; Srivasta *et al*., 1987), around 4–2·8 Ma BP in Iceland (Geirsdóttir and Eiríksson, 1993) and 3–2·5 Ma BP in N. Europe (Shackleton *et al*., 1984). Thus Antarctica should add an interesting new dimension to studies of the development of glaciated landforms over long timespans.

There is a general belief that corries in Antarctica are larger than elsewhere. Walcott Cirque on Mt Lister in Victoria Land is often quoted as being the largest known (16 km wide, with a 3000 m headwall) (Taylor, 1926; Flint, 1971; Hambrey, 1994). The average size of Aniya and Welch's (1981) features in Victoria Land is larger than those of mid-latitudes (though the biggest was only 3·24 km wide). The presence of larger corries in Antarctica seems significant in view of the popularity of ergodic hypotheses in geomorphology, where bigger individuals are often regarded as being older or in a more advanced stage of development.

MOUNTAIN GLACIATION IN THE ANTARCTIC

Antarctica is usually associated with ice sheet activity, but Sugden and John's map of landscape types (1976, p. 202) shows a number of areas of predominantly alpine glaciation, including the Antarctic Peninsula, the Ellsworth and Transantarctic Mountains and various nunatak areas in East Antarctica. Previous studies of corries in Antarctica may not have concentrated on the areas of most intense mountain glaciation. Aniya and Welch (1981) studied Victoria Land where corrie glaciers were probably cold and only weakly erosive by the mid-Miocene (Denton *et al*., 1993), as they are now (Holdsworth and Bull, 1970), although controversial warmer periods have been mooted for the Pliocene (Harwood, 1985; Webb, 1990; Webb and Harwood, 1991). Indeed Sugden *et al*. (1995) dispute the glacial origin of these landforms, interpreting them as little-modified semi-arid valley heads. The Antarctic Peninsula may provide more reliably glacial forms. Here, Linton (1964, p. 96) spoke of 'glacial sculpture on a scale so vast that it can be comprehended only by a decided effort of the scientific imagination', and described what he believed was an advanced stage of consumption of preglacial landforms by mountain glaciation.

The Antarctic Peninsula is one of three uplands which nourished the West Antarctic Ice Sheet before it coalesced over the low-lying area now at its heart. There appears to have been ample opportunity for alpine glaciation during the Oligocene and Miocene. Haynes (1995) reviewed published evidence which indicates that the Oligocene here was characterized by periods of temperate alpine glaciation, sometimes extending to sea level, and the Miocene by alternating wet-based valley and ice sheet glaciation, with the latter becoming more permanent by *c*.4·8 Ma. Some alpine glaciation may have begun in the Eocene, but if so it is likely to have been limited, as there are abundant remains of temperate vegetation.

In high mountains, tectonics may also influence glacial development. The Antarctic Peninsula was formed by Late Triassic to Cainozoic subduction. This died out from the southwest from 50 Ma BP, ceasing around 4 Ma off the northeast coast (Barker *et al*., 1991). Fission track dates from all over the Peninsula suggest two main pulses of uplift at 90 Ma and 40 Ma (Storey, personal communication). The main mountain system therefore probably developed in the Cretaceous and Eocene, prior to the onset of glaciation, though it is conceivable that uplift around 40 Ma could have helped trigger the earliest glaciation. To date, there is little independent

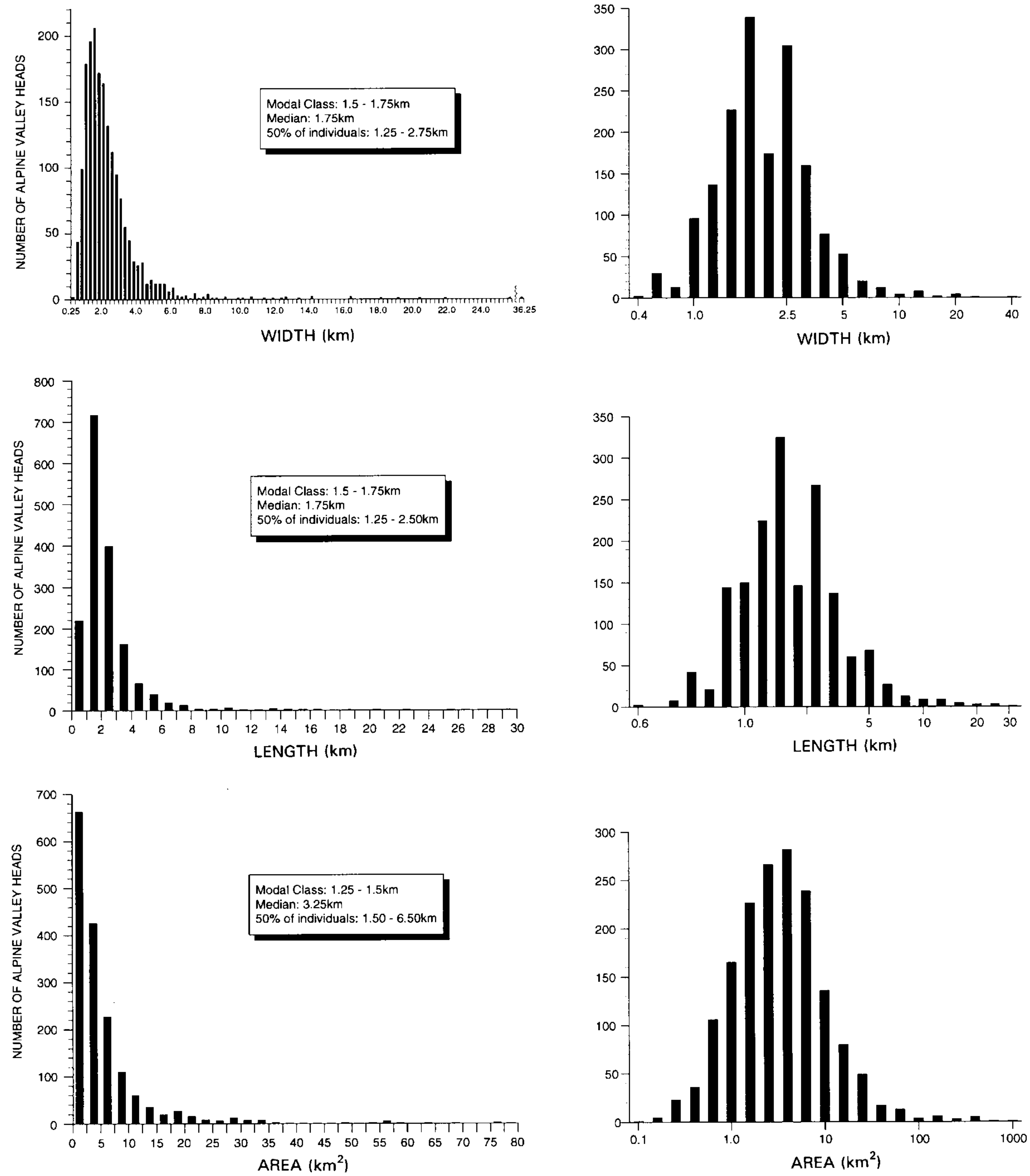

Figure 2. Widths, lengths and areas of alpine valley heads in the Antarctic Peninsula. Column 1 shows the skewed nature of the distributions (NB the 12 largest individuals are not shown on the area graph). Column 2 shows logarithms of the data, demonstrating near-normality when this transformation is applied

evidence of significant differential tectonic change in the area studied during the period of interest to glaciation history.

Present-day ice cover is extensive and the equilibrium line close to sea level, except in the northeast. Most of the corries are still partly ice-filled. Sometimes only the crest of the walls shows above the ice sheet, though in

many areas substantial rockwalls encircle the glaciers. Little detail is known about present glacier thermal regimes. The range of 10 m temperatures at low altitude is from –0·1°C in northwest coast glaciers to –10°C at 70°S, and at high elevation from –12·9°C in James Ross Island (1500 m) to –23°C further south (>2000 m) (Martin and Peel, 1978; Aristarain and Delmas, 1981). In the northwest some glaciers may be wet-based, though elsewhere, outside the main ice streams, small glaciers are likely to be cold. There is a sharp climatic divide a few kilometres west of the east coast between the maritime west and the polar continental east (Schwerdtfeger, 1970).

THE PHYSICAL ENVIRONMENT OF THE ANTARCTIC PENINSULA

The northern part of the Peninsula (Graham Land) is a narrow, 1500–2000 m plateau, thinly covered with cold ice. Its 1000 m scarps are heavily dissected by outlet and corrie glaciers. Linton (1964) hypothesized that fragments of smooth, rounded terrain in Graham Land and Alexander Island are remnants of a rolling preglacial upland with a relative relief of <450 m. To the south in Palmer Land, the Peninsula widens abruptly and the subglacial topography becomes very rugged (Anckorn, 1979; Crabtree, 1981), with 3000 m nunataks projecting above a thick ice dome.

Exposed rocks in the backbone of the Peninsula are dominantly plutonic and volcanic, though there are some sedimentary rocks on the west and east coasts and especially in Alexander Island.

DATA SOURCES

The most complete coverage of the Peninsula is achieved by using satellite imagery. Alpine valley heads were identified on 1:250 000 photographic prints of bands 7, 4 and 6 ERTS MSS images from a variety of dates, band 7 being generally the most useful. This was checked in several sample areas on vertical air photographs (both TMA and FIDASE). A brief assessment of the validity of using satellite imagery as a data source is given elsewhere (Haynes, 1995). Width and length were measured on the satellite images to the nearest 125 m. Unfortunately it was impossible to include depth in the analysis as many of the features are still occupied by unknown thicknesses of ice. Discussion is therefore limited to the planimetric aspects of corrie development. Since distributions of width, length and area were found to be skewed (Figure 2), logarithmic transformations were used for statistical analyses.

The alpine valley heads were assigned to four classes: ‘simple’, ‘complex’, cirque trough’ and ‘secondary’. ‘Complex corries’ included both compound and composite corries as defined by Grove (1958), i.e. ones with subcomponents or tributary corries. ‘Secondary corries’ were the component tributaries of the complex corries. ‘Cirque troughs’ were more elongated features where the alpine valley head continued with no obvious step into a linear trough (Gordon, 1977).

RESULTS

Dimensions of alpine valley heads

The distributions of width and length have an identical median of 1·75 km (Figure 2). Both are strongly skewed towards smaller sizes, but with a long tail of larger examples (for example 9 per cent are >4 km wide and 1 per cent >10 km). Lengths are slightly more variable and less clustered than widths. Since both width and length are well correlated ($r = 0{\cdot}76$), width is used as a convenient and representative measure of corrie size in the following discussions.

The largest complex alpine valley head recognized is Drygalski Glacier (East Graham Land) (Figure 6), which is 36 km wide and 29 km long. The larger features are not evenly distributed over the Peninsula. Those wider than 4 km occur everywhere, but are commonest in Alexander Island (43 per cent) and Graham Land (35 per cent), with fewer found in Palmer Land (15 per cent) and even less in the southeast, along the Lassiter coast (7 per cent). The largest 1 per cent are concentrated in northern Graham Land and Alexander Island (Figure 1).

Comparison with other areas reveals both similarities and important differences. The smallest corries overlap in size with northern hemisphere corries, though medians and modes are larger (Figure 3). The latter

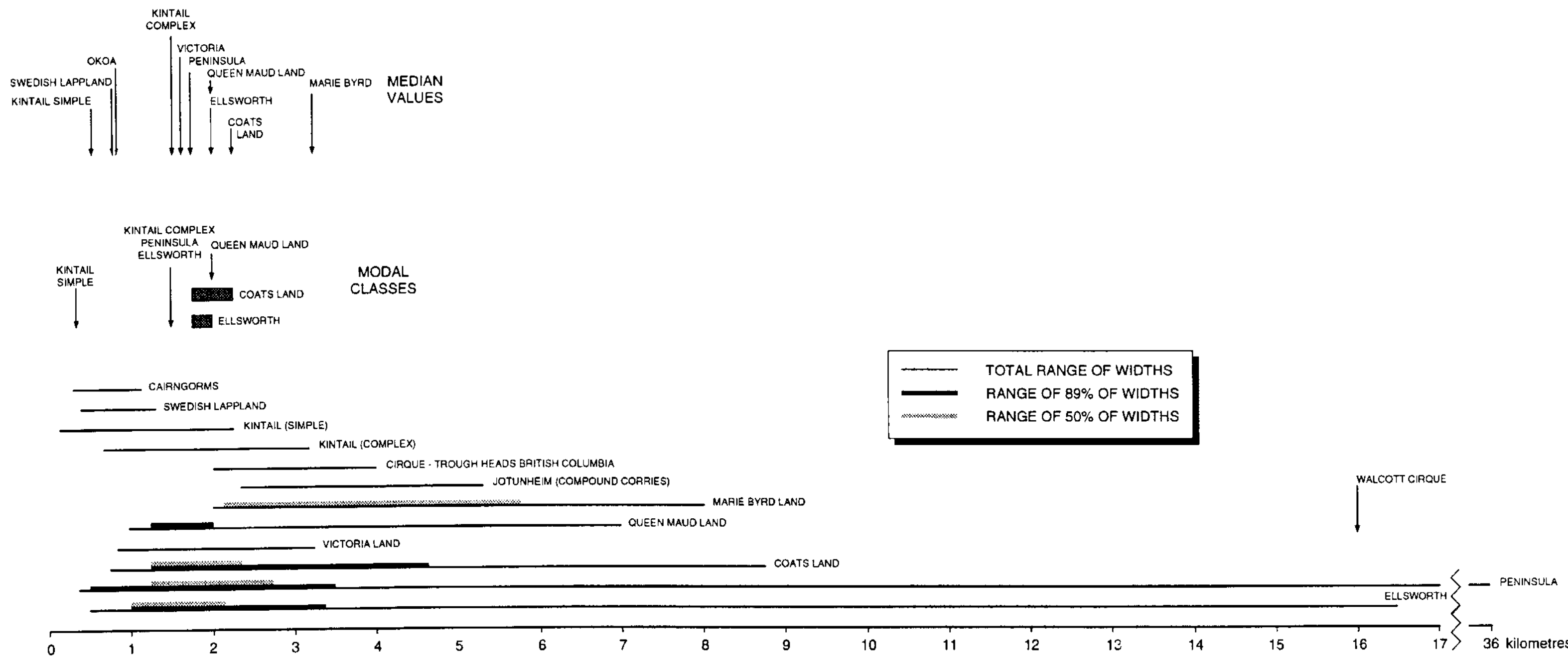

Figure 3. A comparison of widths of alpine valley heads in the Antarctic Peninsula with other areas. The data show total range of values in the samples and some measures of central tendency. Comparative data are from Taylor (1926), Sugden (1969), Andrews and Dugdale (1971), Andrews and LeMasurier (1973), Derbyshire and Evans (1976), Gordon (1977), Vilborg (1977), Aniya and Welch (1981) and Holmlund and Näslund (1994). Northern hemisphere locations are Cairngorms and Kintail (Scotland), Lappland (Sweden), Jotunheim (Norway), Okoa (Baffin Island) and British Columbia. Antarctic locations are Peninsula, Victoria, Ellsworth, Coats Land, Queen Maud Land, Marie Byrd and Walcott Cirque

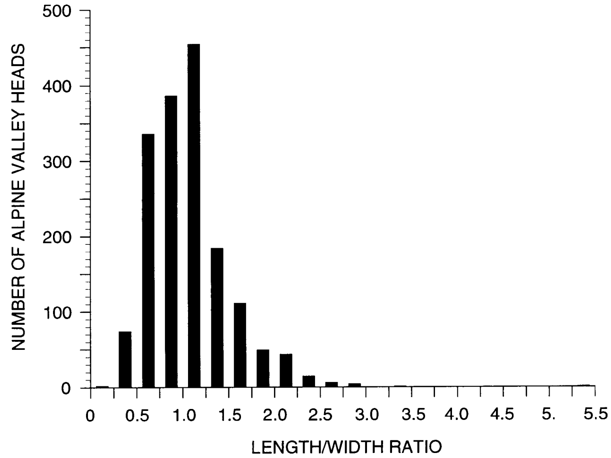

Figure 4. Length/width ratios of alpine valley heads on the Antarctic Peninsula

values are, however, similar to those of Scottish cirque complexes (Gordon, 1977) and to the features investigated by Aniya and Welch (1981) in Victoria Land (though the doubt cast on the glacial origin of the latter should be noted). The largest alpine valley heads in the Peninsula are much bigger than those reported from elsewhere, apart from some other locations in Antarctica (Walcott Cirque (Taylor, 1926), Marie Byrd Land (Andrews and LeMasurier, 1973), Queen Maud Land (Holmlund and Näslund, 1994), the Ellsworth Mountains and Coats Land (Haynes, 1995)).

The shape of alpine valley heads

Length/width ratios. The high correlation between width and length and their identical medians suggest that corries develop an equidimensional planform and maintain this during growth. To investigate this further, length/width (*l/w*) ratios were calculated both for the whole sample and for various subgroups. The *l/w* ratios are strongly clustered around 1·0 (median 1·0, mean 1·03, standard deviation 0·44), representing a roughly circular shape (Figure 4). Despite their larger size, the alpine valley heads found in the Antarctic Peninsula differ little in this aspect of planform from corries measured elsewhere. Others have found a similar clustering around 1·0, but with slightly more bias towards elongation, e.g. N Scotland median 1·08 (Gordon, 1977); Baffin Island 1·3 (Andrews and Dugdale, 1971); Rocky Mountains 0·70–1·33 (Graf, 1976); Victoria Land 1·31 (Aniya and Welch, 1981).

Student's *t*-tests were used to compare the means of the *l/w* ratios of the total sample and of different subgroups. The only subgroups which were significantly different (at the 0·1 per cent level) were cirque troughs, which, as expected, were more elongated (mean $l/w = 1{\cdot}73$), and secondary corries which were slightly wider (mean $l/w = 0{\cdot}95$). To test whether there is any progressive trend towards elongation, as suggested by workers elsewhere (e.g. Derbyshire and Evans, 1976; Gordon, 1977; Aniya and Welch, 1981), *l/w* ratios were correlated with both the square root of area and with width. The sample was also subdivided into five subgroups on the basis of width (<1·25, 1·25–1·75, 1·75–3·5, 3·5–6 and >6 km) and the *l/w* ratios of each compared. The correlations between *l/w* ratio and square root of area and width are poor ($r = 0{\cdot}14$ and $-0{\cdot}15$, respectively). Gordon (1977) found correlation coefficients of 0·23 between *l/w* and corrie volume and −0·23 with width, and Aniya and Welch (1981) found 0·16 with area and −0·3 with width. None of these correlations seems large enough to mean much, presumably due to the clustered nature of the *l/w* data. There is, however, some limited systematic difference between different size classes. Differences are significant at the 1 per cent and 5 per cent levels, respectively, between the *l/w* ratios of the three smaller subgroups, whose means are 1·5, 1·6 and 0·99, respectively, but not between the means of the three largest subgroups, which are 0·99, 0·96 and 0·95.

Planform closure. Evans (1969) regarded planform closure as one of the most important attributes of corrie morphology. He defined it as the range in azimuth of the longest unbroken contour in the corrie walls, though others have used the contour midway between the maximum headwall and lip altitudes, averaging across

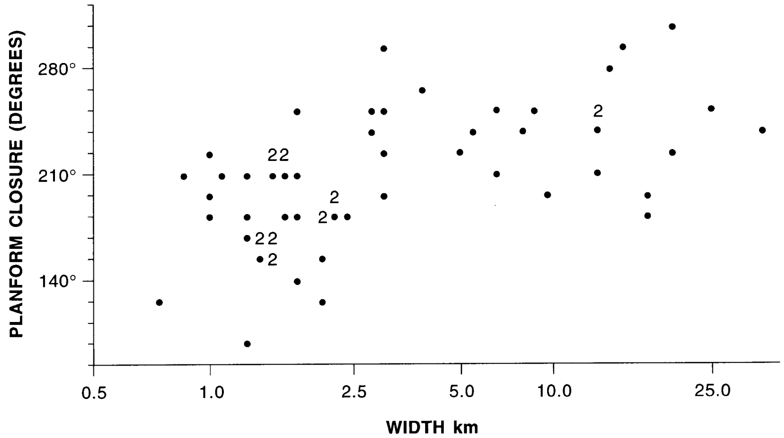

Figure 5. Planform closure of different sized alpine valley heads (numbers on the graph refer to coincident individuals)

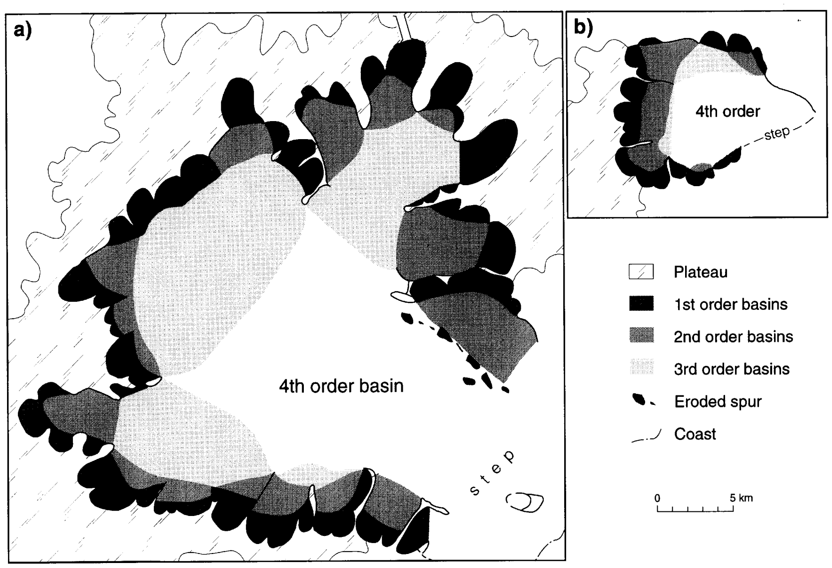

Figure 6. Examples of fourth-order alpine valley heads. (a) Drygalski Glacier, the largest feature found, still has room for expansion into the adjacent plateau. (b) Victoria Glacier. The sequence of basin linkages necessary for ordering was determined using glacier flowlines, which were easily visible on the satellite images

secondary corries (Gordon, 1977). Since plan closure is a time-consuming variable to measure, it was not possible to use the whole sample, so four blocks of terrain were chosen from Graham Land and Alexander Island (Figure 1). These areas were selected because they contain a complete range of alpine valley head sizes (0·75–36 km wide) and are also areas where a substantial part of the corrie walls are above the ice, so that the outline of the middle parts of the walls could be assessed. This sample size was 62. Form lines were drawn on the satellite images and, where possible, on air photographs. The range of plan closures was 102–310° (mean 207°), which overlaps with but extends that found by Evans (1974) in British Columbia (40–245°; mean 139°); Gordon (1975) in N Scotland for corrie complexes (119–264°; mean 173°); and Embleton and Hamann (1988) in Britain and Austria (62–263° with means of 166° and 185°, respectively).

There is some tendency for closure to increase as corries enlarge (Figure 5), though size explains <35 per cent of the variation in closure (correlation of log width with closure, $r = 0{\cdot}58$). This is similar to the results found by Gordon (1975) (closure versus width $r = 0{\cdot}49$; closure versus $\sqrt[3]{\text{volume}}$ $r = 0{\cdot}56$), who suggested that many other more site-specific factors, like lithology, are involved in the determination of closure.

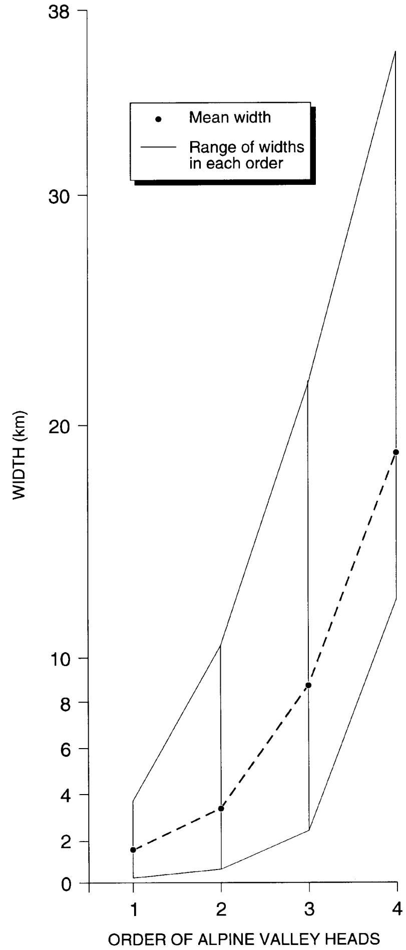

Figure 7. Width of different orders of alpine valley heads

Complexity of alpine valley heads. To investigate branching, the 'Strahler Order' of all the complex alpine valley heads was recorded. Strahler Order was used in preference to Shreve Magnitude as 'generations' of branching were of interest rather than numbers of tributaries. The largest order found was 4 (Figure 6). Although there is a broad tendency for corries to increase in order as they grow (correlation of log width and order $r = 0{\cdot}73$), once they reach widths of *c.* 13 km there is no further increase in order (Figure 7).

DISCUSSION AND CONCLUSIONS: THE DEVELOPMENT OF ALPINE GLACIATION OVER TIME

Planform morphology

Broadly equal rates of widening and lengthening, to maintain an equidimensional shape, are suggested by the clustering of *l/w* ratios around 1·0 and the poor correlation of these with size. Secondary corries often appear to start out as small crenulations on larger corrie walls, and so tend to be wider than average. Presumably these lengthen to assume the more circular form of larger corries. Over the whole sample, however, there appears to be a slight trend towards widening during growth rather than elongation, as there are significant differences between the means of the *l/w* ratios of the three smallest subgroups of corries, which change from 1·15 to 0·99. However, this process reaches a limit as corries approach 3·5 km across, since the means for the three largest subgroups are not significantly different. It is suggested that, while individual simple corries could lengthen slightly as suggested by other authors, divide elimination may often oppose this trend. Loss of divides between

adjacent corries may tend to produce jumps in width by comparison with length, while loss of internal divides in a complex valley head may help to maintain an overall circularity of planform. Thus even the largest features still have *l/w* ratios close to 1·0.

Complexity of alpine valley heads

The literature on corries seems divided as to whether they become simpler or more complex in outline with time. Hobbs (1910, 1911, 1921) suggested that corries become more intricate as they develop. Grove (1958) found large complex corries to be more common than simple ones in Jotunheimen, Norway, and suggested that geological weaknesses in the headwalls and/or inequalities in accumulation influence the flow pattern so that a spiral of activity is begun which eventually forms complex corries. Haynes (1971, p. 162) described corries in the Cairngorms, Scotland, where structural weaknesses have led in one case to an upper step cut out of a corrie wall, and in another to the development of a small tributary corrie which was occupied by an independent glacier in limited glacial stages. Derbyshire and Evans (1976) suggested that more marginal glaciation may increase the likelihood of complexity. On the other hand, Linton (1963) rejected Hobbs' idea of increasing complexity and instead suggested a model stressing rapid elimination of subsidiary divides, especially where the equilibrium line is close to sea level. Evans (1969), too, favoured the view that plan form is simplified by spur elimination and that the more complex outline of larger corries may be due to coalescence rather than 'branching'. Again, study of the very large Antarctic alpine valley heads may shed light on these apparently contradictory views.

In the Antarctic Peninsula, there seems to be a broad tendency for complexity, as expressed by Strahler Order, to increase with size. Figure 7 shows that there is an almost straight-line relationship between order and the *maximum* size of alpine valley heads, whereas the variation between orders is much less with the *minimum* size of alpine valley heads. There is a particularly marked overlap between orders 1 and 2. Thus second-order corries can be very small and one must conclude that the development of irregularities to form primary tributaries and thus second-order basins is a fundamental part of the development of even the smallest corries.

The formation of higher-order basins appears more unlikely. Not only is there a limiting order of 4, but third- and fourth-order basins are grossly under-represented. Consideration of the numbers in each order as a geometric series with N_1 and N_2 as the first two terms (as suggested by Horton (1945)) would predict that there should be *c*. 60 third-order basins (actual number 18) and 27 fourth-order (actual number ten). It is believed that the number of higher-order basins is being continually reduced by internal divide elimination and by external coalescence. The former is particularly likely because internal divides will be attacked from at least two directions at once. Thus, new second-order basins are continually being created, but the majority (*c*. 70 per cent) of these seem to have their internal divides eliminated before the network can progress to become third-order. At the same time, new irregularities may develop in their walls so that first- and second-order status is continually being revitalized. Progressive branching and continued order increase might be more likely if enlargement were dominantly unidirectional, i.e. by lengthening, rather than by both widening and lengthening.

Are there equilibrium forms?

One question about which there has hitherto been little consensus is whether corries develop an equilibrium planform. Hack (1960) suggested that equilibrium in the landscape may result in the development of 'characteristic' or 'limiting' values of morphometric properties and high levels of intercorrelation between them. Both Linton (1963) and Sugden (1969) argued that corries do reach an equilibrium form, while Derbyshire and Evans (1976) suggested that positive feedback is typical of corrie erosion, rather than the negative feedback usually associated with attainment of equilibrium. Gordon (1975) felt that equilibrium forms were not developed in his sample of Scottish alpine valley heads. He acknowledged that the relatively constant *l/w* ratios found by most workers do suggest a dimensionless property, but he found a linear increase in plan closure with increased size and no tendency towards the semicircular equilibrium shape suggested by both Linton (1963) and Sugden (1969).

The much greater duration of glaciation in Antarctica than elsewhere adds another interesting dimension to this debate. In the case of corrie planform, such properties as length, width and area have been found to be well correlated in all studies, so that *l/w* ratios cluster closely around 1·0. This is confirmed even for the largest

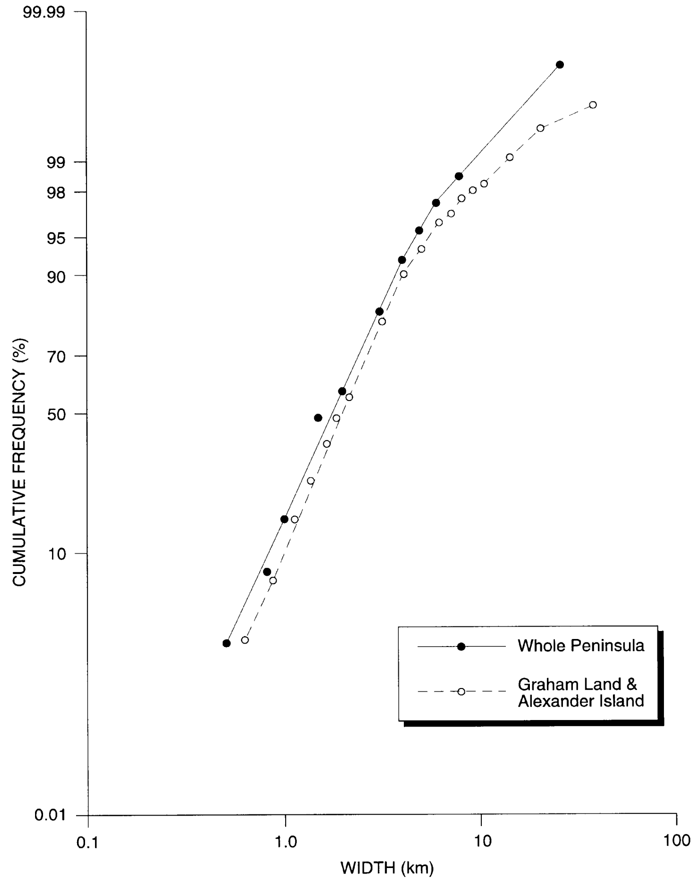

Figure 8. Log *x* probability plots of cumulative frequency distribution of widths of alpine valley heads in the Antarctic Peninsula and in the subareas containing those >10 km. The graphs show log-normality up to widths of 6 and 4 km, respectively. Inflections above these values suggest a deficit of larger examples

features found in the present study, so attainment of a dimensionless form is again suggested. Both order of alpine valley heads and planform closure reach limiting values. In the latter case, the graph of closure against size (Figure 5) flattens out after widths of *c.* 3 km. This is about the size of Gordon's largest corrie complex, suggesting that they were still too immature to demonstrate a limiting value. Nevertheless, this study, like Gordon's, shows very scattered values of closure; for example, the largest feature (36 km wide) has a closure of 240°, a value shared by individuals only 1·75 and 5·5 km wide, while the largest value is for a valley head 20·25 km wide.

The presence of intercorrelation and limiting values of morphometric properties does suggest a tendency to develop a characteristic planform, which can perhaps be regarded as an equilibrium form, though there is still a great deal of individual variety due to site-specific factors. Also, the limiting values are not reached at the same time: that for closure; for example, develops at a width of *c.* 3 km and for order at *c.* 13 km. Unfortunately the present study could not test whether depths and planform morphology develop in phase.

A model for the evolution of alpine valley heads

It is suggested that corries evolve into large, complex alpine valley heads, such as those found in northern Graham Land and Alexander Island. The smallest corries right through to the largest complex alpine valley heads seem to have uniform planimetric properties. Their characteristics overlap with both simple northern hemisphere corries and the complexes recognized by Gordon (1977). Derbyshire and Evans (1976) argued that,

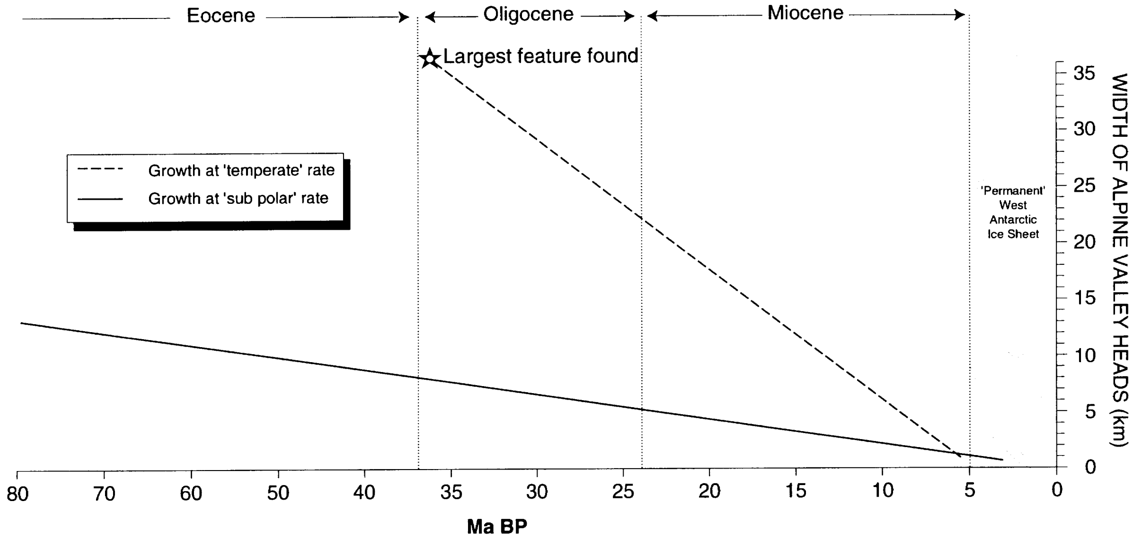

Figure 9. Hypothetical timespans required to form alpine valley heads of different widths. Assumptions are an initial valley half as wide as the smallest corrie and continuous alpine glaciation until the formation of the 'permanent' west Antarctic Ice Sheet. The temperate erosion rate is 1·0 mm a^{-1}. This is both an overall erosion rate found by Larsen and Mangerud (1981) for a corrie in Norway and is also the rate for widening produced by their estimated rockwall retreat of 0·5 mm a^{-1}. The subpolar erosion rate is 0·2 mm a^{-1} (the highest rate found in Baffin Island corries by Andrews (1972)). This does not look capable of forming the majority of the features in the time available

despite the great size range of corries in British Columbia and Tasmania, straight-line graphs of cumulative frequencies of corrie volume plotted on log *x* probability paper suggest a regular log-normal distribution and thus a single type of landform which could grow steadily in size. They attributed a similar graph of Gordon's data from Scotland, which had a slight break of slope at 1 km^3, to a mixed population including both corries and complexes, which they therefore suggested were different phenomena. When this test is applied to the Antarctic Peninsula, both as a whole and only those areas containing the largest examples (Figure 8), a smooth log-normal distribution is revealed up to widths of *c*. 4–6 km, but there are inflections at greater widths. While this may mean that larger features are examples of a different type of landform, the present author prefers the interpretation that the largest features are numerically under-represented in the landscape. Certainly the distribution remains smooth over larger sizes than Gordon's and this part of the curve includes corrie complexes as well as simpler features. Larger features get progressively fewer in number due to coalescence and also because of destruction by other agencies, like ice sheet erosion.

The clustered locations of the largest alpine valley heads in the Peninsula are consistent with this interpretation. The five largest occur in northern Graham Land, where significant erosion of many of the headwall crests during ice sheet stages has been prevented by the narrowness of the plateau and its thin cold ice cover. Thus the imprint of mountain glaciation has remained dominant in landform evolution, as suggested by Linton (1964). Here, survival of parts of Linton's preglacial surface suggests that lateral coalescence has been incomplete, allowing some at least space to grow, without too much interference from their neighbours (Figure 6a is a good example). After long periods of time (or sooner if the original corries were very closely spaced), external coalescence should destroy the surrounding land surface and reduce the numbers of large alpine valley themselves. Only remnants of their headwalls will remain, cut into by the smaller corries which were originally their lower-order tributaries. This stage appears to have been reached in some cases.

Numbers of large alpine valley heads decline southwards into Palmer Land, as the influence of the main ice sheet increases. Presumably this is due both to decreased lengths of time available for mountain glaciation and to more destruction by ice streams and shifting ice divides. Although Alexander Island was an ice sheet centre in its own right, its mountains may not have been completely submerged in ice (Clapperton and Sugden, 1982; Kennedy and Anderson, 1989), so longer periods of alpine glaciation may have occurred. Also, mountain

groups which develop their own radial flow patterns within ice sheets retain alpine glaciation forms, rather than the valley patterns typical of ice sheet glaciation (Haynes, 1977).

It seems relevant to consider whether the dimensions of the larger features are compatible with the timescale available for their development. Haynes (1995) argued that the majority of the alpine valley heads in the Antarctic Peninsula were initiated during the Late Miocene. The largest features considered in the present study could be older, perhaps early Oligocene. Comparison of Figures 2 and 9 gives an indication of the possibilities. Larger initial valleys would give a younger age than suggested on Figure 9, as would a non-linear erosion rate due to significant amounts of coalescence of adjacent corries, while more intermittent glaciation would push initiation back perhaps into the Eocene. The linear erosion rate used, rather than a non-linear rate which might be typical of coalescence, seems possible at least for some of the largest features, e.g. Dryglaski Glacier, since some of the preglacial surface survives (Figure 6). These estimates do seem to give results of a credible order of magnitude, which ties in with what is known of the duration of glaciation in the area, but require independent testing.

Through time there must be continual addition of new corries to the population as well as the continued enlargement of the existing ones. Some new corries are created by branching, while others develop on new sections of valley wall which are eroded by ice streams and then exposed to alpine glaciation at lesser glacial stages. The positively skewed distributions of sizes and the limits to the degree of branching suggest that the opposed processes of development of complexity (as geological variations are encountered) and of simplification (by divide elimination) are both fundamental and concurrent processes of alpine valley head development.

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